C-CORE

Geological Evidence of Iceberg Groundings and Related Seafloor Process in the Hibernia Discovery Area of Grand Bank, Newfoundland

C.F.M. Lewis and J.V. Barrie

Presented to the Symposium on Production and Transportation Systems for the Hibernia Discovery.

Conference Paper
C-CORE Publication 81-8
January 1982

Geological Evidence of Iceberg Groundings and Related Seafloor Process in the Hibernia Discovery Area of Grand Bank, Newfoundland

C.F.M. Lewis and J.V. Barrie

Presented to the Symposium on Production and Transportation Systems for the Hibernia Discovery.

Conference Paper
C-CORE Publication 81-8
January 1982

C-CORE
CENTRE FOR COLD OCEAN RESOURCES ENGINEERING
MEMORIAL UNIVERSITY OF NEWFOUNDLAND
ST. JOHN'S, NEWFOUNDLAND, A1B3X5, CANADA
TELEPHONE [redacted] (709) 737-8354

The Centre for Cold Ocean Resources Engineering (C-CORE) was established at Memorial University of Newfoundland in St. John's in 1975. Its initial funding was provided by the Devonian Group of Charitable Foundations of Calgary. Ongoing funding now comes from government and industry.

The Centre's mandate is to undertake research that will assist the safe and orderly development of Canada's resources in cold and ice frequented oceans. C-CORE's main concentration of research is on ice, its properties, detection and behaviour, on the interaction between oil and ice, and on seabed engineering.

TABLE OF CONTENTS

	Page
Abstract	1
Introduction	2
Field Investigations	2
Ice-Seabed Interaction	5
Regional Geological Setting	7
Surficial Geology of the Hibernia-Ben Nevis Area	9
Sediment Stability	12
Grand Bank Ice Scour	15
Attributes of the Holocene Ice Scour	18
Scour Abundance and Water Depth	18
Scour Abundance and Sediment Facies	20
Seabed Disturbances and Scour Width	22
Scour Depth	22
Summary and Conclusions	27
References	30
Acknowledgements	32

LIST OF FIGURES

		Page
Figure 1	Index maps of the Grand Bank	3
Figure 2	Underwater photographs of a small grounded iceberg	4
Figure 3	Examples of well-defined ice scours and their variety in a mud basis on the Labrador Shelf	6
Figure 4	Generalized geological cross section across the Northern Grand Bank between Hibernia and Bay Bulls	8
Figure 5	Contors of sand thickness over Tertiary semi-consolidated bedrock in the Hibernia - Ben Nevis area	10
Figure 6	Surface sediment facies in the Hibernia - Ben Nevis area	11
Figure 7	Geological cross-section of the northeast edge of the Grand Bank in the Hibernia area	13
Figure 8	Huntec DTS resolution seismic profile	14
Figure 9	Sidescan image	16
Figure 10	Sidescan image of the northeast Grand Bank in 102m water depth	17
Figure 11 a,b	Scour per unit area vs water depth	19
Figure 12	Histogram of scour per unit area	21
Figure 13	Histogram showing variation of ice scour attributes	23
Figure 14	Histogram of average of maximum scour depths	25
Figure 15	Extreme value plots for maximum scour depths in northeast Grand Bank area	26

GEOLOGICAL EVIDENCE OF ICEBERG GROUNDINGS AND RELATED SEAFLOOR PROCESSES IN THE HIBERNIA DISCOVERY AREA OF GRAND BANK, NEWFOUNDLAND

C.F.M. Lewis
Atlantic Geoscience Centre
Geological Survey of Canada
Bedford Institute of Oceanography
Dartmouth, Nova Scotia

J.V. Barrie
C-CORE, Centre for Cold Ocean Resources Engineering
Memorial University of Newfoundland
St. John's, Newfoundland

ABSTRACT

Interpretation of the northeastern area of Grand Bank seabed based on high resolution seismic reflection profiles; side scan sonar imagery; bottom photography, sample and current metering; and engineering boreholes generally supports the surficial geology model of Fader and King (1981) and shows further evidence that the Hibernia area seabed is subject to iceberg scouring and intermittent sediment transport. Thin discontinuous sand and gravel unconformably overlie Tertiary semiconsolidated siltstone and sandstone. A lag gravel terrace, probably related to late Wisconsin low sea level occurs between 100-110 metres on the northeast Grand Bank margin. Alternating sand bars and lag gravels parallel the slope contours above the terrace. Below it a thin continuous fine sand facies partially buries a degraded relict iceberg furrowed surface. Sand waves, megaripples and wave-induced ripples indicate intermittent sediment transport in shallower water on and above the terrace. The Tertiary unconformity appears to be over-consolidated probably due to erosion, subaerial exposure and dessication during periods of glacial low sea levels.

A sparse population of relatively fresh looking ice scours comprising linear and curvilinear furrows and circular pits occurs throughout the region and is believed to represent the cumulative record of iceberg impacts within the past 10,000 years (Holocene) when late Wisconsin low sea level had risen sufficiently to allow icebergs to drift onto the Bank. Ice scour depths, widths, and ice-related seabed disturbance range from 0 to 6.5 metres, 3 to 124 metres, and 0 to 15% respectively. The extreme value distribution predicts, for example, one scour 2.7 m deep or deeper in a survey line 100 km long between water depths of 100 and 150 metres. Between 140 and 70 metres water depth on the margin of the Bank there is an upslope decrease in scour depths, widths, abundance and seabed disturbance. This is thought to arise as a result of a decrease in iceberg size and flux toward the Grand Bank margin away from the major iceberg source - the main branch of the Labrador current flowing around the northeast corner of Grand Bank. Scour depths may also be limited in shoaler water by the occurrence of the over-consolidated Tertiary unconformity near the seabed surface and by intermittent sedimentary infilling.

INTRODUCTION

Less than 100 m below sealevel and extending more than 400 km eastward into the Atlantic Ocean, Grand Bank lies exposed to Greenland icebergs drifting southward in the cold Labrador current. The number of bergs fluctuates widely depending on the flow of the current, but on average 400 bergs each year drift into the Grand Bank area according to census reports by the International Ice Patrol, summarized by Murray (1969) and Dinsmore (1972). Most bergs are swept with the main branch of the current around the eastern flank of the Grand Bank while others are carried by the western branch down the Avalon Channel close to the Island of Newfoundland (Fig. 1). Many bergs, however, deviate from these drift routes under the influence of variable currents and strong winds on to the bank itself (Blenkarn and Knapp, 1969; Lewis and Benedict, 1980) where some of the larger ones ground to load the seabed and to displace its surface sediments.

The Hibernia discovery area, located in 80 m of water on the northeast margin of the Grand Bank (Fig. 1) is clearly vulnerable both to the iceberg scouring threat and to the disturbance by currents and waves from ocean-and-storm-generated water movement. As yet little is known of the origin of the surficial geological units and the degree to which seabed sediments are mobilized and redistributed by modern hydrodynamic processes. This latter aspect, the question of suspension and transport of shelf sediments, is an outstanding problem of shallow marine sands in general according to a recent review by Walker (1979). Thus original research into Hibernia seabed problems will be of widespread scientific and engineering interest.

During 1980 the above questions were addressed by four major research activities: by the extension of an established geological mapping program onto the northern Grand Banks (Fader and King, 1981); by detailed mapping of the surficial geology in the Hibernia area; by modelling potential current shear and sediment transport; and by evaluating iceberg scours (iceberg disturbed seabed) and iceberg intrusions. Known collectively as the Hibernia Sediments Program this work is led by scientists from the Atlantic Geoscience Centre of the Geological Survey of Canada and the Centre for Cold Ocean Resources Engineering (C-CORE) of Memorial University of Newfoundland. Research is ongoing and the initial results are still being reduced. At this interim stage we undertake a preliminary review and interpretation of the surficial geology, sedimentary processes and the nature, distribution and significance of ice scours of the northeastern sector of Grand Bank in general and the Hibernia area in particular.

FIELD INVESTIGATIONS

From the results of a major regional geological cruise of CSS HUDSON completed May 1980 (Fader, 1980), Fader and King (1981) delineated the principal surficial geological units on the northern Grand Banks and explained their development. Their contribution is based on an extensive net (Fig. 1) of airgun and Huntec DTS (Hutchins et al, 1976) seismic reflection profiles, BIO sidescan (Jollymore, 1974) sonograms of 1.5 km nominal swath width, in addition to a limited number of grab samples, cores and bottom photographs.

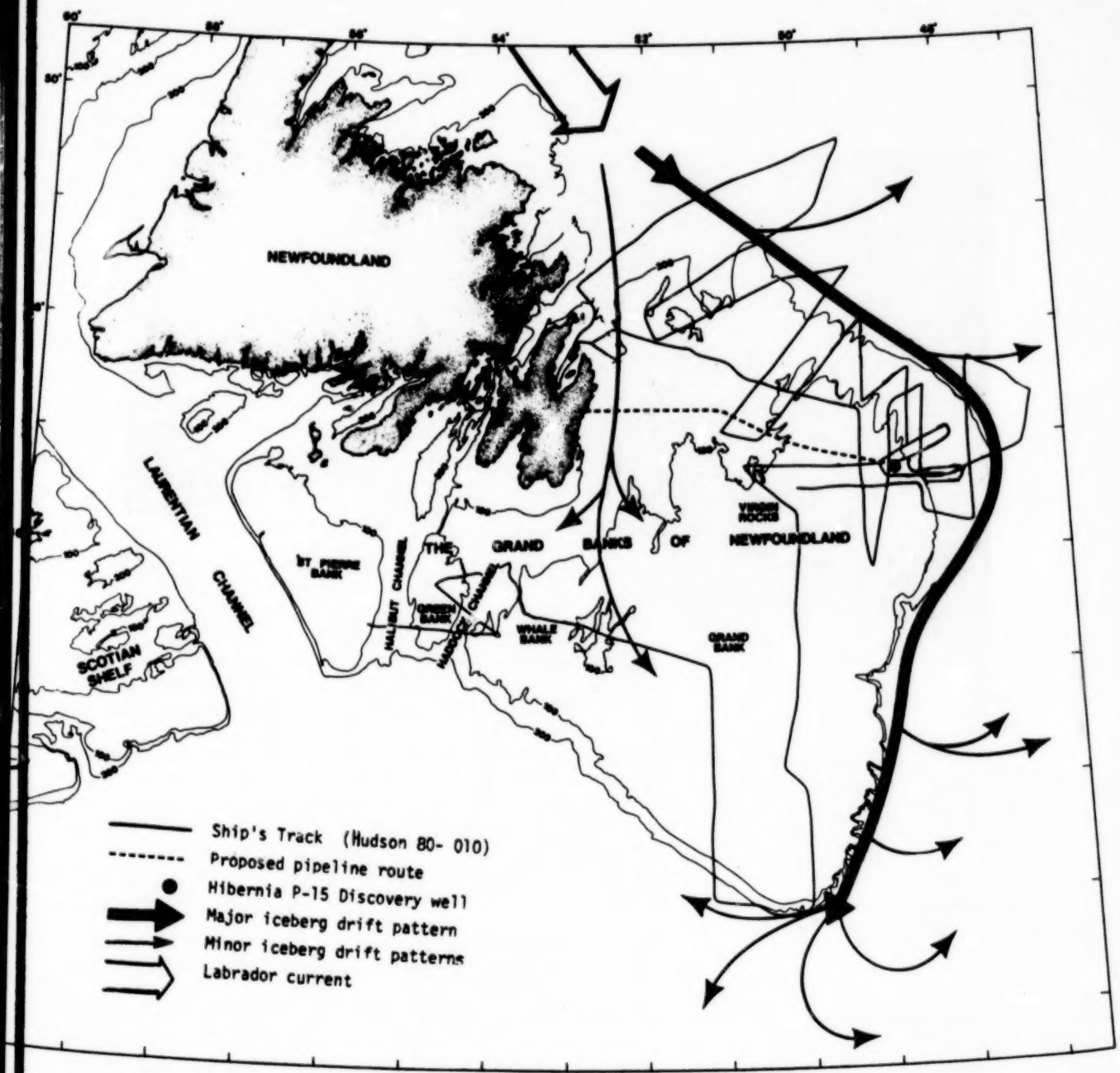


Figure 1. Index map of the Grand Banks showing the 100 and 200 m isobaths, survey tracks for HUDSON cruise 80-010, the Hibernia discovery well (from Fader and King, 1981) and the major iceberg drift routes (from Dinsmore, 1972).

Figure 2. Underwater photograph of a small grounded iceberg showing the formation of an ice scour in unconsolidated sediment. The enbankment alongside the excavated furrow and adjacent to the ice keel is approximately 80 cm high. This 'ice island' fragment (a type of tabular iceberg) had drifted aground in the nearshort zone of Byam Martin Island in the Central Arctic archipelago. (Courtesy Dr. P. McLaren, GSC Photo 202842-Q).

The genesis and mobility of the sediment cover in a 65 by 70 km area encompassing the Hibernia and Ben Nevis wellsites was examined in June 1980 using MV POLARIS V, a survey vessel under charter to Mobil Oil Canada Ltd. (Amos and Barrie, 1980). The POLARIS survey included a 4 km grid of bottom samples with selected high resolution Klein 100 kH$_z$ sidescan transects (0.4 km nominal swath width), bottom photographs, suspended sediment determinations and near-bottom profile measurements of current velocity.

A further cruise on the POLARIS V vessel in October 1980 increased the quantity of detailed surficial geological and iceberg scour data within the Hibernia-Ben Nevis research area by completing a systematic pattern of O.R.E. sidescan (0.75 km nominal swath width) and Huntec DTS profiles at 4 km intervals. These data were supplemented with regional geophysical tie lines, gravity coring and seabottom photography.

In addition we have benefited from reports of surveys and studies commissioned by Mobil Oil Canada Ltd.; in particular three borehole reports by Geocon (1975) Ltd., six wellsite reports by Geomarine Associates Ltd. (4) and NORDCO Ltd. (2), and results of bottom current measurements by MacLaren Plansearch Ltd. The prime contractor to Mobil Oil for wellsite reports and for navigational-geophysical services aboard M.V. POLARIS was McElhanney Surveying and Engineering Ltd.

ICE-SEABED INTERACTION

Drift ice in the ocean, loads and disturbs the sediment when its undersurfaces (keels) bear down upon the bottom under the influence of swell, tide etc., or drag across the seabed under the influence of currents, strong winds or pressure from other ice. Two kinds of drift-ice features are significant agents in seabed disturbance - icebergs and sea ice ridges.

Ridges originate by the rafting of sheets of sea ice under pressure and normally produce keels of a few metres or few tens of metres deep, rarely deeper than 40 m even in Arctic Ocean waters. Thus they are significant in seabed disturbance on shallow shelves and in nearshore waters (Pelletier and Shearer, 1972; Reimnitz and Barnes, 1974; Kovacs and Mellor, 1974; Wadhams, 1975; Shearer and Blasco, 1975; Wahlgren, 1979; Lewis, 1978). On the other hand thick glaciers and ice shelves which calve in deep water produce large icebergs with drafts commonly in the range of 100 to 200 m (Dinsmore, 1972) or larger (Murray, 1969). These keels are the principal agents for ice-related disturbance of sediments on the offshore banks of eastern Canada.

The effect of small ice keels intersecting unconsolidated sediment in the central Arctic archipelogo has been observed by P. McLaren and colleagues (Fig. 2) using SCUBA gear (McLaren 1977). Linear grooves in the sediment which he called ice scour tracks marked the passage of grounding icebergs. Embankments of displaced sediment were heaved up onto either side of the groove, possibly by shear failure and lateral displacement or by compression and extrusion of material from beneath the keel. A similar embankment encircled the back side of the keel where it had come to rest, delineating circular depressions called craters. Similar processes but on a larger scale have been inferred and described from features seen in side scan sonar records on the shelves of the western Grand Banks (King, 1976), Belle Isle Bank and Labrador Shelf (Harris and Jollymore 1974; Harris, 1974) and from Baffin Bay (Lewis et al., 1979). Ice-formed linear grooves and circular depressions are also described from the Grand Banks by Fader and King (1981) as furrows and

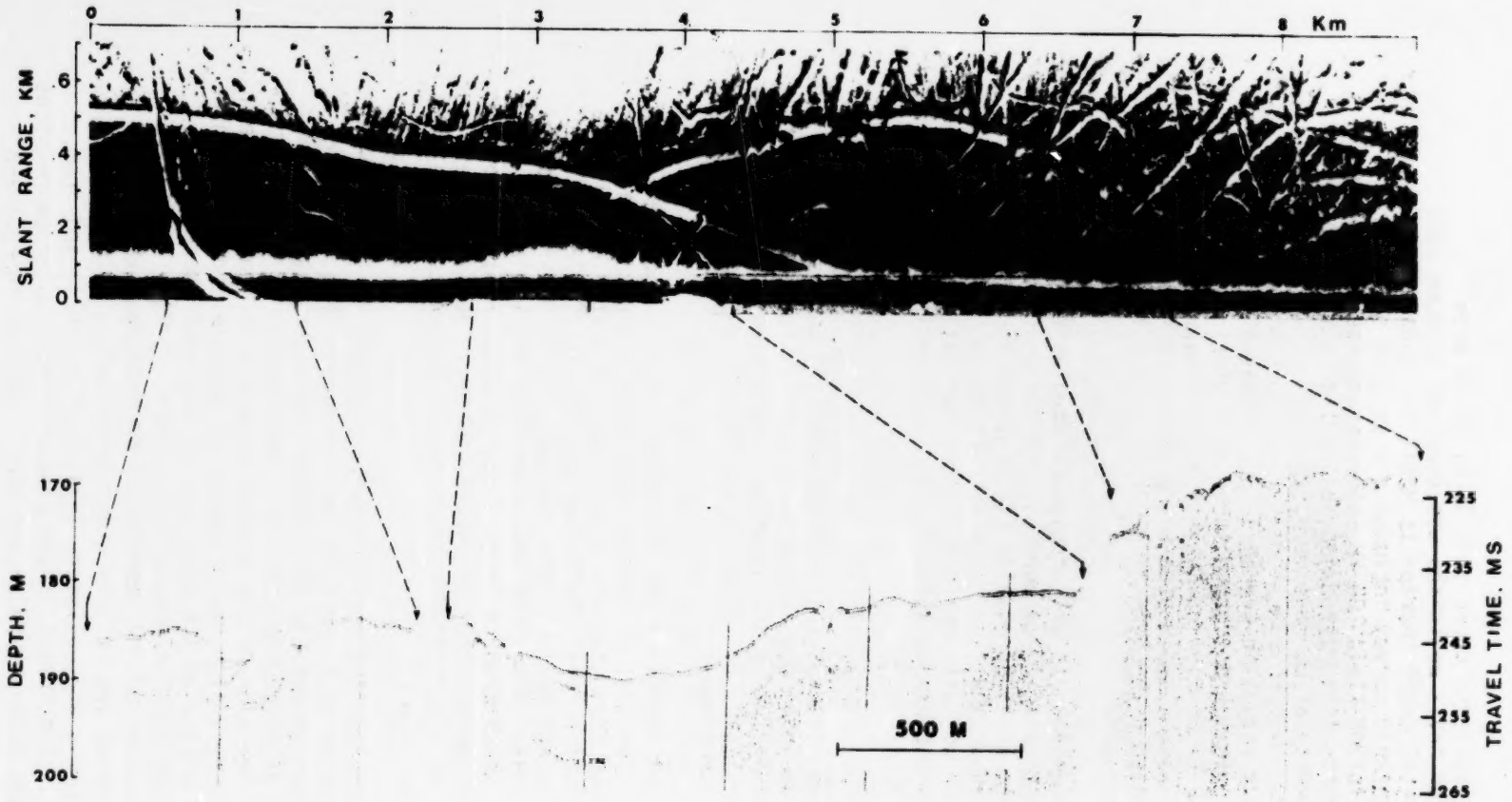


Figure 3. Examples of well-defined ice scours and their variety in a mud basin on the Labrador shelf. Ice-scoured furrows and craters are shown in plan and section. The top panel is a plan-view image of the seafloor taken from one channel of the BIO 70 KHz sidescan sonar. Note that this original record is compressed in the along-track (horizontal) direction by a factor of 2.5 relative to the cross-track direction. The induced distortion rotates the trend of linear features slightly toward the perpendicular to the track of the tow-fish and enhances the width of features in the cross-track direction. The lower panel shows vertical sections through the seabed (Huntec DTS high resolution seismic records) that correspond (indicated by dashed tie lines) to portions of the lower edge of the sidescan image. Cross sections of several ice scours and the resulting extent of ice keel disturbance in the stratified surficial mud unit can be discerned.

pits respectively. The composite records in Fig. 3 illustrate in plan and section a wide variety of ice scour forms that occur on the Labrador shelf.

The results of laboratory simulation of the ice scour process are discussed by Chari and Peters (1981) in a companion paper of this Proceedings.

In this paper we have chosen to use the term ice scour as a general expression for all types of seabed disturbance by drift ice. The specific morphologic types of ice scours - linear to curvilinear grooves and circular depressions - are referred to as furrows and pits respectively following the usage of Harris and Jollymore (1974), King (1976) and Fader and King (1981).

REGIONAL GEOLOGICAL SETTING

King and Fader (1980) divide the bedrock geology of the northern Grand Banks into three units. The first unit consists of a sequence of undifferentiated late Precambrian, metamorphic rocks which are an extension of the rocks on the Avalon Peninsula. Further offshore Unit 2 comprises a succession of well indurated sedimentary rocks ranging in age from Cambrian to Mid-Silurian. Both Unit 1 and Unit 2 are overlain by sedimentary rocks of Cretaceous and Tertiary age (Unit 3) on the eastern portion of the Grand Banks extending to the edge of the continental shelf.

A cross section between Bay Bulls, Newfoundland, and Hibernia, illustrating the bedrock geology, is shown in Figure 4. The profile occurs along a proposed route for a pipeline from the Hibernia area to the island of Newfoundland. Surficial cover over the Precambrian and majority of the Palaeozoic bedrock in the Avalon Channel is generally less than 2 m thick and has been moderately disturbed by iceberg scouring (Fader and King, 1981). This thickness is within the limit to which iceberg keels can penetrate. Offshore 100 km from the coast the surficial sediments thicken into Downing Basin (Fig. 4), a zone of fine sands and silts of glaciomarine origin that have not been disturbed greatly by icebergs. Here sediment thickness varies between 5-10 m and rarely exceeds 50 m. Closer to the Hibernia area the surficial sediment thins to a range of 1-5 meters over the semi-consolidated Cretaceous - Tertiary bedrock and becomes much "harder" (i.e. more reflective) as shown by the Huntec DTS seismic record.

Fader and King (1981) have proposed a preliminary geological history for the formation of the surficial units in the northern Grand Bank area. At the time of the last glaciation most of the Shelf in this area was covered with glacial till and glacio marine sediments. These sediments rest unconformably on Tertiary "bedrock", which consists of semi-consolidated siltstones, mudstones and sandstones dipping very slightly to the east. At the end of the Pleistocene a large portion of Grand Bank was subaerially exposed. The late Wisconsin-Holocene transgression commenced at about 15,000 years BP (Fader and King, 1981) causing a rapid redistribution of the Quaternary deposits into something approaching the present day pattern of sediment distribution. On the Scotian Shelf and the western Grand Banks of Newfoundland the pre-Holocene low sea level stand has been estimated to lie between 110-120 m below present sea level (King 1970; Fader et al., 1981). Fader and King (1981) indicate that a low sea-level stand in the Hibernia area may have occurred at the same water depth (110-120 m). A terrace with an upper elevation of 100 m occurs along the northeastern edge

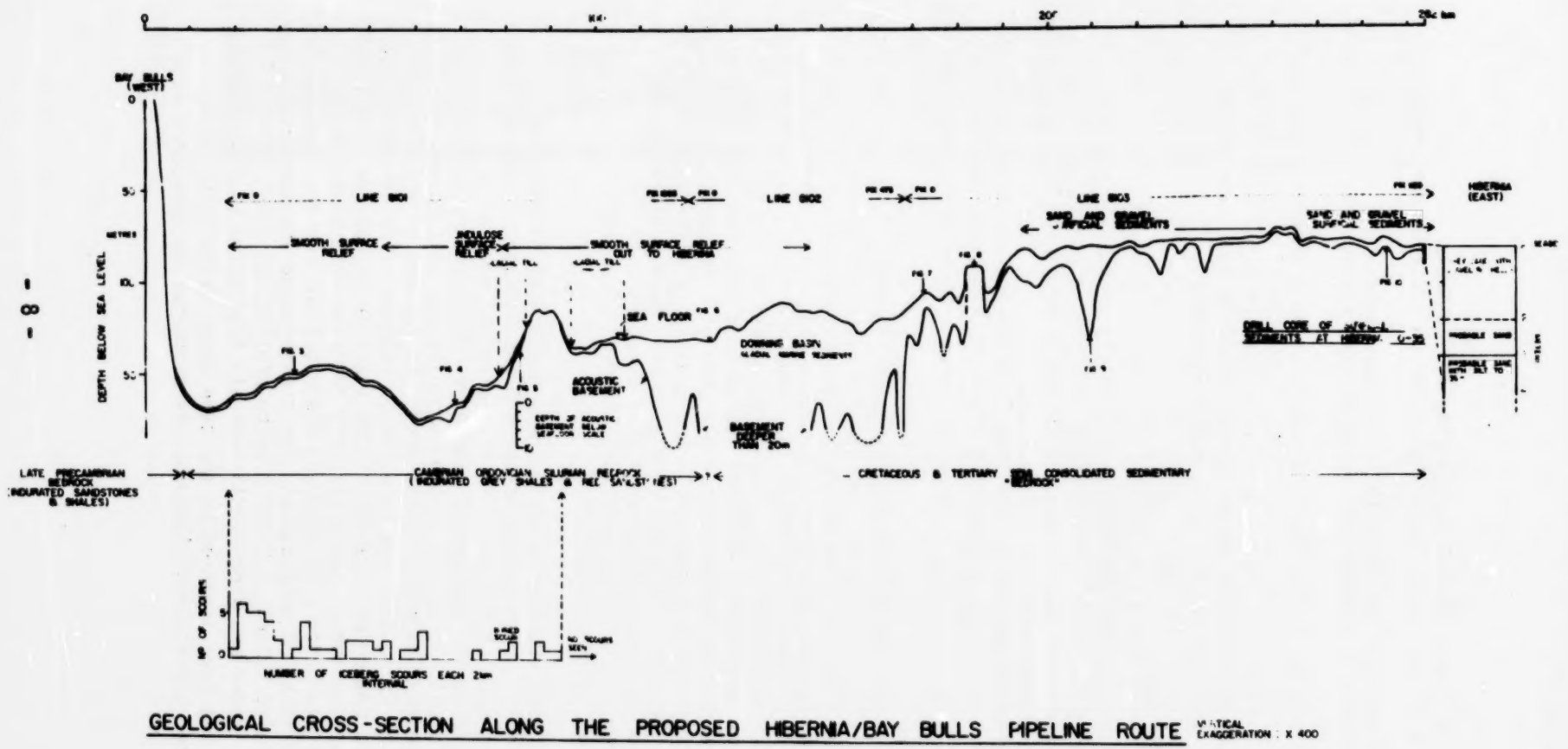


Figure 4. Generalized geological cross-section across the northern Grand Bank between Hibernia and Bay Bulls. Based on King and Fader, (1980) and Geomarine Project Report (80-1001).

of Grand Bank in the Hibernia area. This may be an erosional feature representing the late Wisconsinan low stand of sea level.

The Tertiary age of the semi-consolidated sediments below the unconformity as interpreted by Fader and King (1981), has been confirmed. J. Bujak (personal communication, 1981) has identified marine dinoflagellate fossils of Tertiary age in samples collected in the Ben Nevis and Hibernia engineering boreholes from beneath the unconformity.

Holocene sediments are essentially compact medium to fine grained clean sands with pebbles, shells and gravel. The Tertiary unconformity, because of a period of subaerial exposure, is probably a partially-cemented hard surface as can be seen in the borehole information from the Hibernia/Ben Nevis region (Geocon Hibernia O-35, Hibernia B-08 and Ben Nevis I-45 Reports, on contract to Mobil Oil Canada, 1980). In both the Hibernia O-35 and Ben Nevis I-45 boreholes a high penetration resistance was encountered at the unconformity surface breaking the core barrel in the Hibernia borehole and necessitating relocation of the Ben Nevis borehole. At the Hibernia B-08 borehole this unconformity surface seems to occur near the seabed coinciding with a strong reflector on the Huntec DTS profile. Below the hard layer (of unknown thickness), representing the unconformity, the Tertiary silts and sands are semi-consolidated and mainly uncemented. An isopach map showing the thickness of sand above this unconformable surface is shown in Figure 5.

SURFICIAL GEOLOGY OF THE HIBERNIA - BEN NEVIS AREA

In the northeastern part of the study area, in depths greater than 110 m (the sublittoral zone of the Holocene sea), the seabed was intensely scoured by grounding icebergs that calved from the retreating Late Wisconsinan ice sheet. These features are interpreted from sonogram records which show discontinuous lineations representing partially buried iceberg scours (furrows) beneath a thin sand cover. This has been defined as Zone 1 by Fader and King (1981). At the western extreme of this zone the character of the buried scours (furrows) becomes less clear and the surficial sediment cover thinner (Fig. 5). Fader and King (1981) define most of this area as Zone 2, a continuous zone of fine sand. More detailed higher resolution side scan sonar coverage shows that a portion of this area (Zone A, Fig. 6) has irregular, poorly defined lineations, which can be interpreted either as buried iceberg scours or truncated Tertiary beds at or near surface. A small area of continuous fine sand (Zone B) similar to Fader and King's (1981) Zone 2, showing no lineations, forms a transitional zone between Zone A and Zone C (Fig. 6) north of 46° 46'N. Megaripples have been identified in isolated patches of these zones, having wavelengths from 10 to 50 m. Seabed photography from all sources show no wave-induced ripples.

A large central zone running north-south between Hibernia and Ben Nevis (Zone C, Fig. 6) is an area of sand ribbons on lag gravel. This zone forms the surface of a large part of the 100 m terrace. There is little indication of sediment thickening in areas of the sand ribbons (Fig. 5) though Fader and King (1981) noted that sand ribbons partially fill shallow depressions on the gravel surface and smooth the seabed profile. The surficial sand and gravel is usually less than 1 m thick (Fig. 5) and probably represents a thin lag lying on the Tertiary unconformity. The sand cover increases in lateral extent to the north.

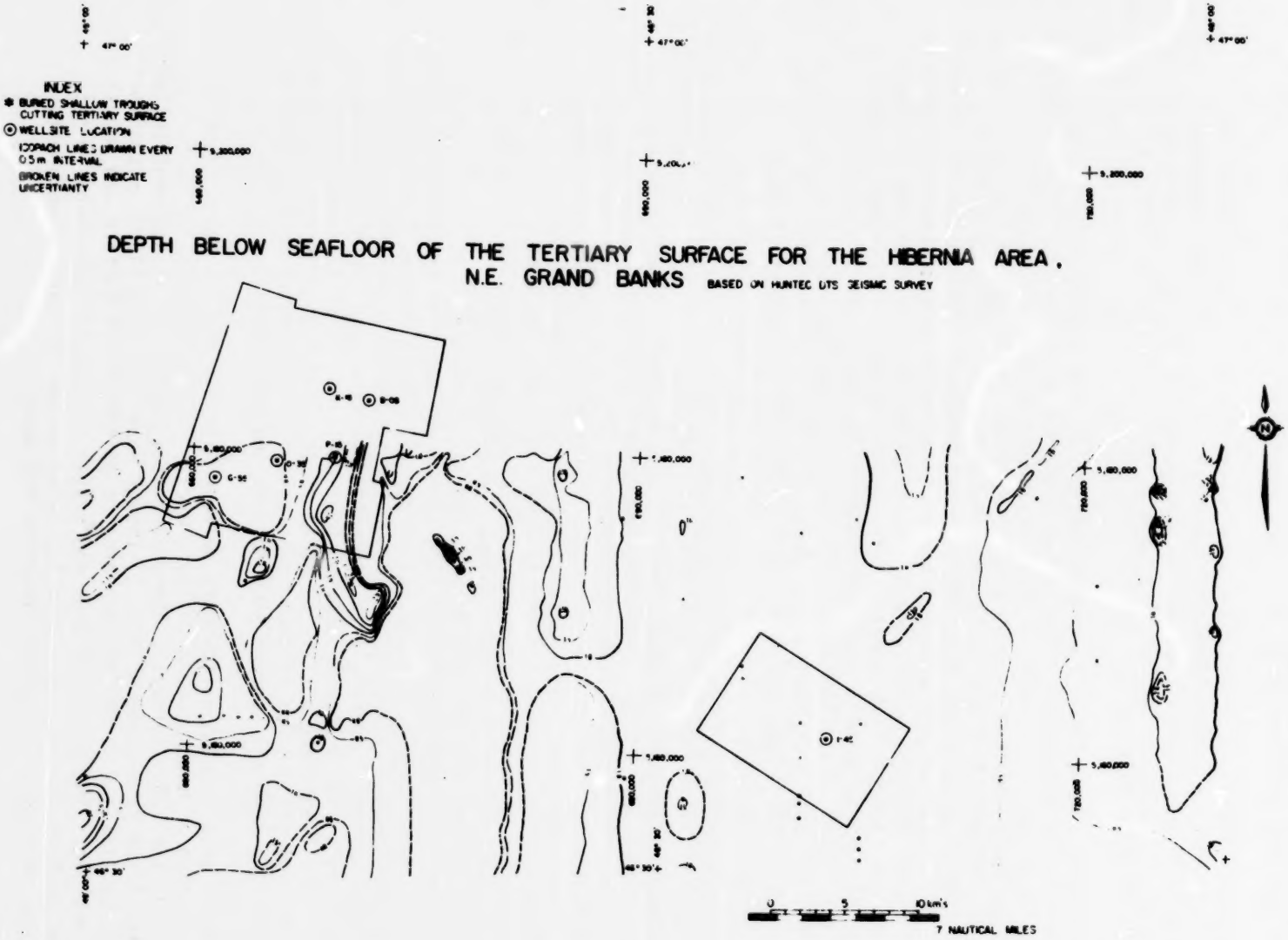


Figure 5. Contours of sand thickness over Tertiary semi-consolidated bedrock in the Hibernia - Ben Nevis area. The contour interval is 0.5 m.

Figure 6. Surface sediment facies in the Hibernia - Ben Nevis research area; A - A' is the trace of the cross section as Fig. 7.

Arcuate sand waves of up to 400 m wave length and 1000 m crest length (Amos and Barrie, 1980) occur normal to the sand ribbons showing a direction of migration from north to south. Megaripples are associated with the sand waves on the flanks of sand ribbons and are orientated in the same direction. Photographs taken by Fader (1980) in this zone during April (1980) show a sediment distribution of sand and gravel and fresh wave-formed ripples lapping on the gravel lag. The photographs show degradation of the ripples by browsing organisms and a later set of photographs taken in June of the same year (Amos and Barrie, 1980) show no rippling.

West of the 100 m terrace in the Hibernia area, zones of well rounded lag gravel (Zone E and G) with shell debris are aligned north-south alternately with zones of well sorted sand (Zones D and F) possibly over gravel (Fig. 6). This general area falls into Zone 4 of Fader and King (1981). A change in slope beginning at the Zone C boundary (Fig. 7), at approximately 100 m, indicates the transition between two terraces. Zone D, the Boundary Sand, is confined to this slope with the eastern gravel lag (Zone E) boundary situated at the upper terrace edge.

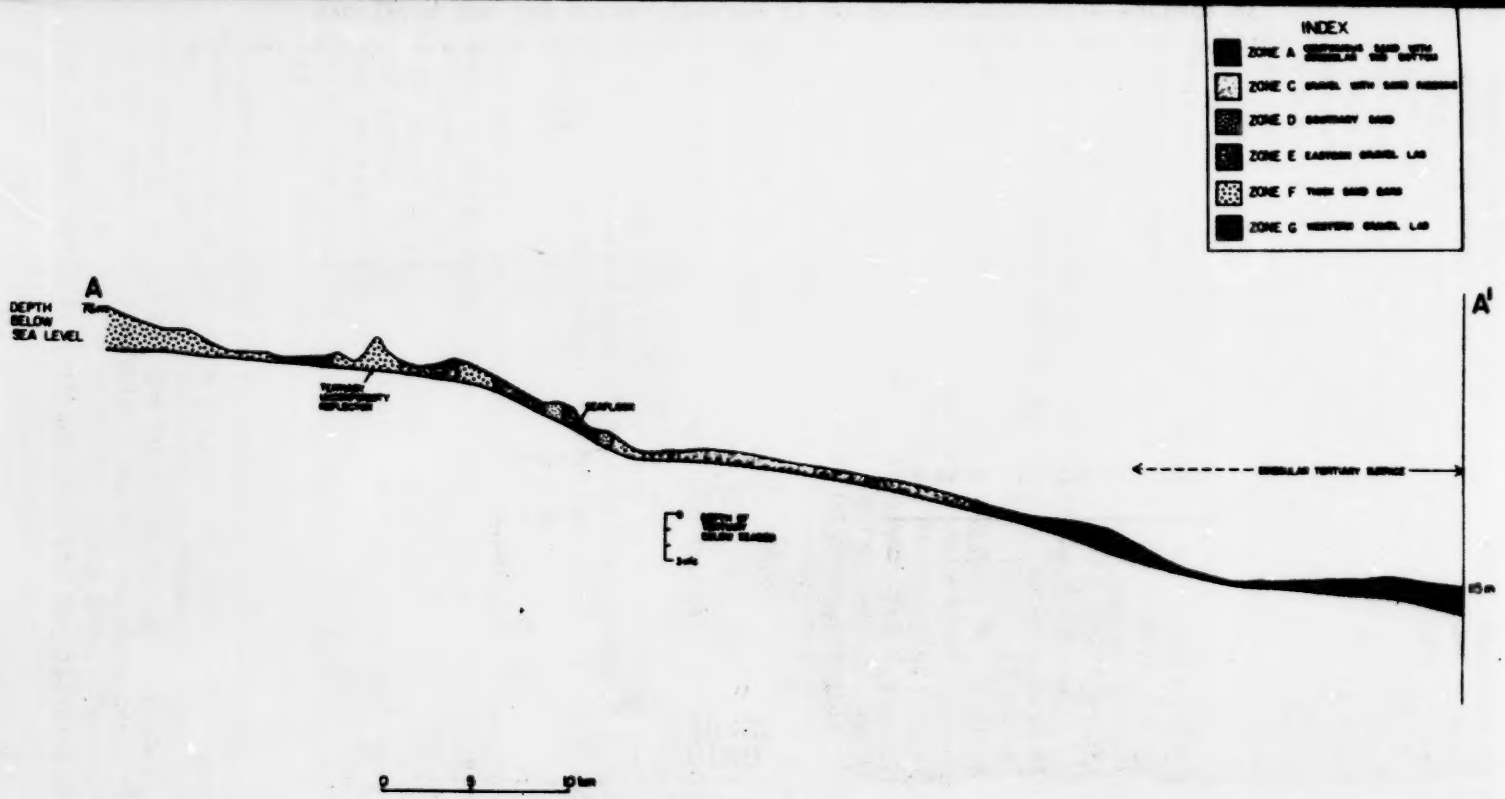
Associated with the Boundary Sand is a discontinuous area of sand waves. Upslope from the Boundary Sand, large fields of megaripples are associated with the sand to gravel transitional areas only on the western edge of the sand bars (Zone F). Arcuate sand waves in the centre of the narrower sand bands are also evident. Wave-induced ripples as seen from photographs, occur generally over the areas of sand but seem to be short term bedform features. Photographs of benthic forms indicate periodic current activity and sediment instability in this zone.

The thickness of the gravel lag in Zone E and G is generally less than 1m (Fig. 5). The alternate areas of surficial sand show thicknesses of greater than 3 m in many places (Zone F), thickness generally increasing to the west and north of the Hibernia area (Figs. 5 and 7). These are primarily seabed bathymetric high features as shown by the Huntec DTS seismic profiles. In Figure 8 the Huntec DTS seismic record shows sand thickening to over 2 m in the sand area (Zone F). These bar-like features could be partly relict or reworked ancient beach deposits of the early Holocene sea and partly bedforms in equilibrium with the present or past ocean environment. They may be significant in determining the early Holocene geological and sea level history of the area. If the time of sea level rise can be dated, the time frame for iceberg scouring will be further refined.

The sequence of geological and bedform facies changes is similar to the pattern found on the southeast African Continental Shelf (Flemming, 1980). Here the pattern is interpreted as being modern in response to specific wave and unidirectional longshore current-controlled regimes with wave domination in shallower waters. In the Hibernia area there is evidence for a similar strong unidirectional current regime with possible wave domination in shallower waters. The problem in the Hibernia area is whether the present distribution of sediments is related to modern current and wave action or whether the distribution is relict.

SEDIMENT STABILITY

In water depths greater than 110-120 m the seabed environment is relatively stable as seen from geophysical survey records and bottom photographs. Sediment



EAST - WEST GEOLOGICAL CROSS - SECTION of the HIBERNIA AREA

Fig. 7. Geological cross-section of the northeast edge of the Grand Bank in the Hibernia area. The inflection (increase in seabed slope) just at the left of centre at about 100 metres water depth is the top of a pronounced terrace, believed to mark a position of the late Wisconsinian low sea stand that trends NNW through the area.

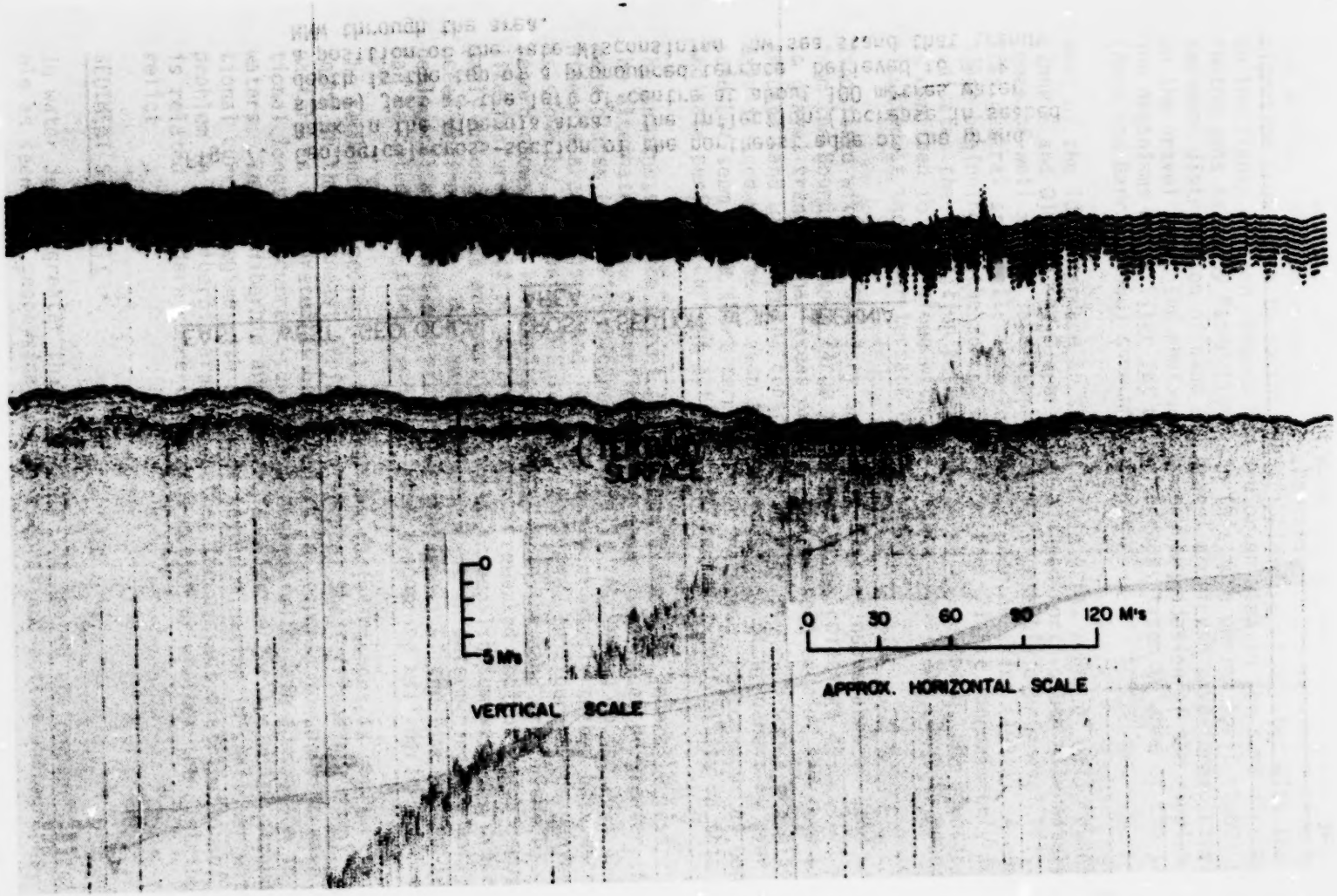


Fig. 8. Huntec DTS high resolution seismic profile showing a sand bar (Facies F) overlying the lag gravel (Facies E) on the unconformable surface of Tertiary semi-consolidated bedrock.

transport is probably negligible. Above 110-120 m the stability of the seabed depends on the interpretation of which features on the seabed are relict and which are modern. Small scale wave-formed ripples found on the thin surficial sands which overlie the lag gravels certainly indicate modern sediment transport and instability of surficial sands. Sand waves are only generated at current velocities of about 60 cm/s and sand ribbons in currents of 100 cm/s (measured at th sea surface) or greater. The residual seabed shear velocity measured during June (Amos and Barrie, 1980) plus current information collected 1 m above the seabed in the Hibernia area, from March 1980 to December 1980, are an order of magnitude less than the velocities needed to form sand waves.

From work undertaken in the Middle Atlantic Bight region of North America it was concluded that current velocities sufficient to form annual (short term response elements) megaripples and to move sand waves (long term response elements) were generated only four to five times a year on an average, by storm surges (Swift and Freeland, 1978; Gadd et al., 1978). The megaripples in this area of the American Atlantic Shelf are short term response features tending to be erased in the quiet summer months by browsing benthic organisms (Swift et al., 1979).

On the Grand Banks a similar hypothesis may explain the bedform morphologies though it is possible that the frequency of storm generated currents is less. The existence of large fields of megaripples indicate that currents capable of transporting sediment occur at least once every few years. The sand ribbons could well be relict features dating back to lower sea levels and higher current energies. Further interpretation cannot be made until the sedimentological and current measurement data are fully analysed.

GRAND BANK ICE SCOURS

Two populations of ice scours are recognized in the northern Grand Bank region (Figs. 9 and 10). A partially buried iceberg-furrowed surface and a set of fresh-looking recent furrows and pits have been described by Fader and King (1981). A third type of feature consisting of buried notches that resemble furrow cross sections is recognized on Huntec DTS profiles from the Polaris cruise.

The partially buried iceberg-furrowed surface occurs only below the 100 m terrace in water deeper than 110 m. The surface is characterized as a dense pattern of degraded furrows that is expressed on sonograms as a network of randomly discontinuous lineations (Fader and King, 1981). This pattern is continuous with and grades into an intensely ice-scoured seabed in water greater than 200 m deep on the northeast Newfoundland shelf. These features are interpreted as relict ice scour populations that formed over 10,000 years ago when sea level was about 100 m lower.

A sparse population of fresh-looking iceberg furrows and pits (Fig. 9) is superimposed on the partially buried iceberg-furrowed surface. Clearly younger, this population is believed to represent the accumulated seabed impacts of icebergs throughout the Holocene period of higher sea levels, or the last 10,000 years approximately. These ice scours occur in all water depths examined (60 m to 160 m) in the northeast Grand Bank. The furrows are elongated linear to curvilinear features that are believed to originate as the keels of drifting

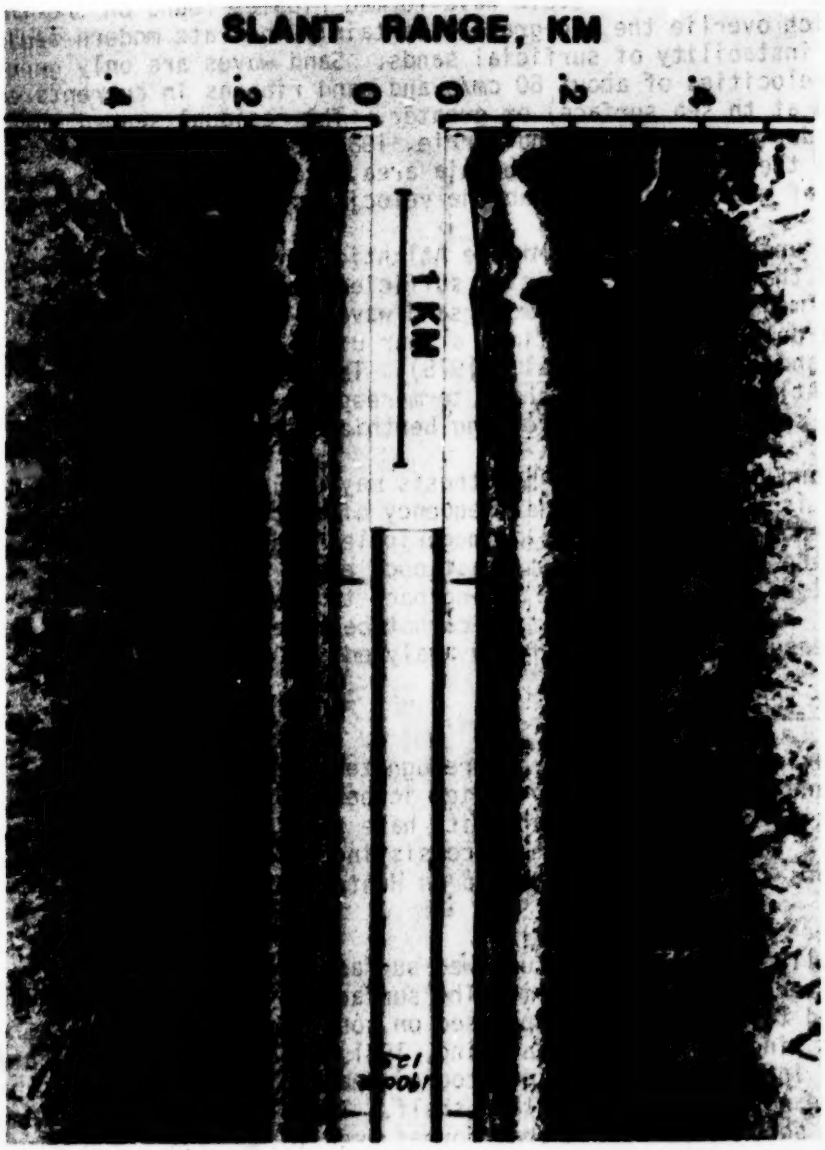


Fig. 9. Sidescan image showing two fresh-looking ice scours on the slope of northeast Grand Bank. The wide straight ice-scour furrow with a hook-like termination and the narrow sinuous furrow (lower right) are superimposed on a mottled surface representing an older generation of degraded and partially buried furrows. The old surface was probably active more than 12,000 years ago when sea level was reduced and icebergs were common from local (Newfoundland) glaciers. The position of the image is 47° 20'N, 48° 34'W in 142 m water.

Fig. 10. A sidescan image of the northeast Grand Bank in 102 m water depth showing alternating areas of lag gravel (dark tone areas indicating a high degree of acoustic backscatter) and sand ribbons (light tone areas indicating smoother bottom and low backscatter values). At left the sand infills and obliterates part of a sinuous ice-scour furrow. The position of the image is 46° 33'N, 48° 11'W.

bergs drag bottom. Their maximum lengths are unknown though some have been tracked for 8 km. Most scours are less than 1 m deep and may range from a few metres to over 75 m in width. The pits are circular isolated depression up to 100 m in diameter. They may be discontinuous furrows or represent areas where an iceberg keel has come to rest, hard aground (Fader and King, 1981).

The existence of buried notches cutting the Tertiary unconformity is interpreted from deep-towed Huntec high-resolution seismic profiles. The notches occur (Fig. 5) widely in the Hibernia-Ben Nevis area from beneath the sand bars in shallow water across the gravel lag terrace to beneath the continuous fine sand in deeper water. The designation of these features as iceberg furrows is tenuous at present, based only on their morphologic similarity to furrows in cross section. Among the possibilities for their origin are that they may have resulted from sea-ice scouring in shallow nearshore water of the late Wisconsinan and early Holocene sea or they may represent a subaerial drainage system that was developed on Tertiary sediments during previous periods of exposure.

Attributes of the Holocene Ice Scours

The variation of ice scour abundance, width, depth and seabed disturbance have been invesigated as functions of water depth and sediment facies. Two data sets, derived from the HUDSON and POLARIS cruises respectively were analyzed independently. The statistical significance of the variations has not been established. At this interim stage the trends indicated and the inferences drawn are preliminary, suggesting relationships or models for future testing.

The HUDSON (Fig. 1) data set is based on 871 km of BIO sonograms and Huntec profiles in the northeastern sector of Grand Bank sector bounded by 46^{o}N, 48^{o}N, 47^{o}W and 50^{o}W. The presence or absence of ice scours was determined for each 2 km (10 minute) section of the sonograms. When present the number of ice scour occurrences, aerial percent of seabed disturbed by ice, and the maximum scour width were evaluated. The maximum scour depth was also measured, with a minimum resolvable depth of 0.3 m on the Huntec profiles.

The POLARIS data set consists of 12,500 km of O.R.E. sonograms and 1100 km of deep-towed, Huntec high resolution seismic profiles in the Hibernia-Ben Nevis research area. Ice scours identified on these sonograms were plotted directly on the surficial geology map (Fig. 6) from which their relative abundance (densities) were determined with respect to sediment facies and water depth. Extreme scour depths (greater than 1 m) were measured on the Polaris Huntec records.

Scour Abundance and Water Depth

The number of scour occurrences in each data set (HUDSON and POLARIS) were normalized with respect to seabed area before plotting histograms of mean relative abundance in successive 20 m intervals of water depth (Figs. 11 a, b). Relative abundance is the number of scours per unit area (i.e. scour density) expressed as a percentage of the sum of the scour densities. This treatment overcomes the problem of comparing areas that have been surveyed with

Figure 11a

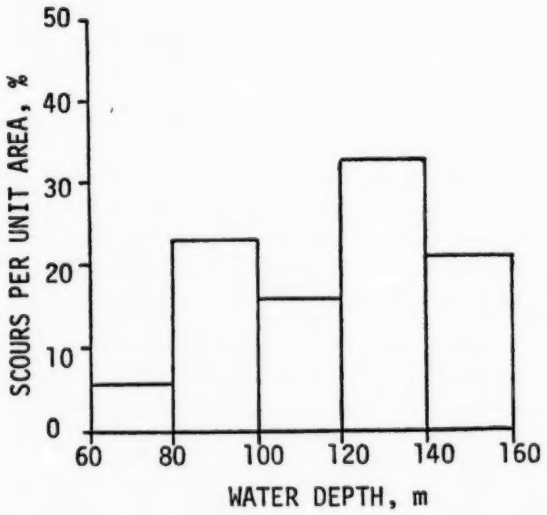


Figure 11b

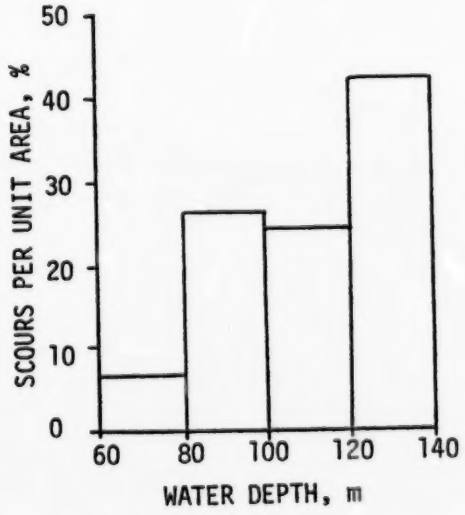


Fig. 11 a, b. Scours per unit area vs. water depth for the northeast Grand Bank region (a) and the Hibernia - Ben Nevis research area (b) (Fig. 6). The first histogram is based on 871 km of BIO sidescan imagery from HUDSON Cruise 80-010 (Fig. 1) east of longtitude 50°W. The second histogram is based on 15,700 km of O.R.E. sidescan data in the research area.

sonars of different sensitivity. The pattern of variation in both data sets is similar between 60 m and 140 m water depth. This supports our feeling that an adequate representation of the relative scour density has been obtained.

The greatest abundance of scours occurs in the 120 m to 140 m class and the lowest abundance occurs in the shallowest class, 60 m to 80 m. There is a general trend of increasing scour abundance with increasing water depth, to 140 m, then a decrease in the next deeper class. This differs from the expected trend as in the Labrador Shelf example (Fig. 3) where scour density increases upslope. The latter trend is expected because the population of drifting icebergs is usually made up of numerous small bergs and rather few large bergs (International Ice Patrol, in Gustajtis, 1979). Assuming that small bergs have shallower keels and that large bergs have deep keels there must be a greater number of keel contacts with seabed in shallower waters than in deeper waters. However this does not appear to be the case for the northeast Grand Bank. Two factors could be at work. First we note that because the seabed slopes gently downward in a northeasterly direction the deeper isobaths are closer to the major iceberg drift route around the Grand Bank (Fig. 1). This deeper seabed north of the Bank may be more frequently scoured because it is closer to the local source of bergs where the flux of deep-keeled bergs could be larger than the flux of shallower keels onto the Bank. The downturn in scour density in the 140 m to 160 m interval (Fig. 11a) may reflect an absolute decrease in the frequency of deeper keels. The second factor that contributes to reduced scour density in shallower waters is related to seabed type, sediment mobility and scour preservation as discussed in the next section.

Scour Abundance and Sediment Facies

The count of ice scours mapped in the Hibernia-Ben Nevis locale (Fig. 6) was organized and normalized by the area surveyed in each sediment facies. The relative abundance of ice scour densities in the Hibernia - Ben Nevis sediment types is shown in Fig. 12. Most of the counted ice scours are iceberg furrows.

Sediment facies E, the eastern lag gravel, carries the greatest number of scours, 30% relative to all other facies. The other lag gravel facies, C and G, carry moderate but substantial numbers of scours also, between 12% and 15% of the total. As expected the scour density is lowest in the most mobile sediment facies, the boundary sand (D) and the sand bars (F) where the relative scour abundance is less than 7%. In contrast the deepest water sand, facies A, carries the second greatest number of scours, 21%. This sand, unlike its counterparts D and F in the shallower water, shows few bedforms and carries little evidence of recent mobility under the influence of storm-or ocean-generated current shear.

It seems clear that the density of ice scours depends on sediment type. It appears that mobilization and transport of sand after ice impact degrades and infills iceberg furrows and pits selectively thereby reducing preferentially the scour density in the sandy facies as compared with the gravel facies, (Fig. 10). This process appears to be most prevalent in the shallower waters (less than 100 m) of the Hibernia - Ben Nevis region where storm-generated bottom currents are

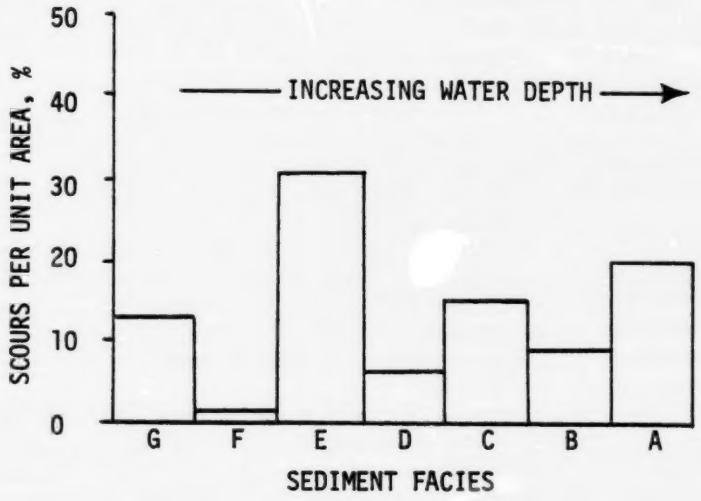


Fig. 12. Histogram of scours per unit area for various sediment facies in the Hibernia - Ben Nevis research area (Fig. 6). A = continuous fine sand, B = transitional fine sand, C = ribbons on lag gravel, D = boundary sand, E = eastern lag gravel, F = sand bars, and G = western lag gravel.

expected to be more intense and more frequent than in the deeper water facies. Clearly a situation of differential ice scour preservation could contribute to the anomolously low values for overall scour abundance in the shallower water as noted in the previous section.

The presence of discrete sand and gravel facies in a particular area, as for example around the Hibernia wellsite, together with the assumption of random ice-seabed contact presents some possibilities for evaluating and linking the relative rates of ice scouring and sediment mobilization. If sand and gravel were equally ice scoured we would infer little or no sediment transport in the period following ice-seabed interaction. On the other hand substantial sand remobilization would be inferred where the scour density in gravel significantly exceeded that in sand. Conceivably, with appropriate theory and methodology, it should be possible to infer the rate of one process given the rate of the other.

Seabed Disturbance and Scour Width

A visual estimate of the percentage of seabed area that was disturbed by iceberg furrows and pits and a measure of maximum furrow width were determined for each sample area on the BIO sonograms of the HUDSON data set. Averages of the two parameters were taken for each 20 m increment of water depth and displayed in histograms (Fig. 13 a, b). The largest average seabed disturbance (2%) occurs in the 120 m to 140 m depth interval. The maximum disturbance observed was 17% in the same interval. The smallest average disturbance is found in the shallowest depth interval, 60 to 80 m. Many sample areas showed no disturbance at all.

The distribution of the seabed disturbance is nearly identical with the scour abundance distribution in Fig. 12. This suggests that aereal disturbance is largely controlled by scour density. The slightly greater proportion of seabed disturbance as compared with scour abundance for the 140 m to 160 m class may be due to the occurrence of wider scours in deeper water (Fig. 13 b).

The average of the widest scours increases uniformly with increasing water depth, rising from 24 m in the 60 m to 80 m depth class to 43 m in the 140 m to 160 m class. The total range of all measured values for maximum scour widths runs from 3 m to 124 m. The regular increase in the width distribution is just what one might expect in a normal population of icebergs with a wide range of draft. The smaller bergs which ground in shallower water have less mass, less volume and presumably narrower keels than do the larger bergs. Hence the narrower scours should occur in shallower water.

Scour Depth

Scour depth is the vertical distance below the undisturbed seabed to the lowest point in an ice-scour profile. In practice the seabed datum is inferred from the level of undisturbed ground beyond the heaved-up sediment in the scour embankments.

Scour depths are difficult to measure with normal echo sounding equipment on the Grand Bank where waves and swell induce vertical oscillations up to several metres amplitude in the seabed profiles. These effects tend to mask and obliterate ice scour profiles most of which are less than 1 m deep. By using records from the heave compensated Huntec DTS scour depths could be resolved to 0.3 m for this study. The maximum depth was measured for each 10 minute or 2 km (approximately) interval of the Huntec profiles along HUDSON tracks (Fig. 1) in the northeastern

Figure 13a

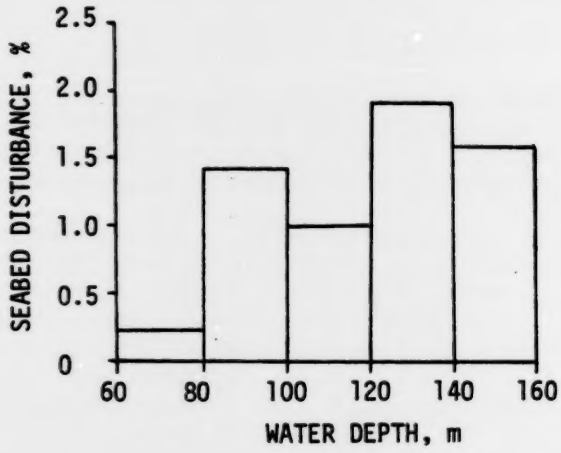


Figure 13b

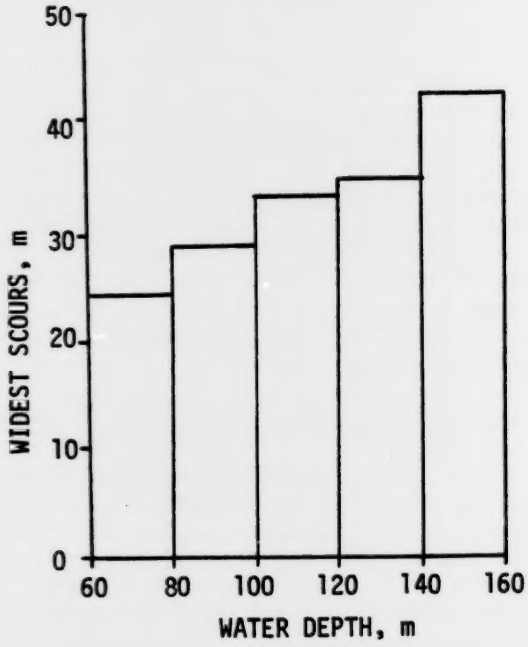


Fig. 13 a, b. Histograms showing the variation of ice scour attributes; the percentage seabed disturbance (a), and the average of the widest scours (b) vs. water depth for the northeast Grand Bank. The attributes were measured from 516 (a) and 178 (b) sample areas respectively in the BIO sonograms east of longtitude 50^{o}W and north of 44^{o}N (Fig. 1).

region of Grand Bank. A scour depth measurement was determined for each sonogram sample area that registered ice-related disturbance though many maximums were of virtual zero depth (i.e. less than 0.3 metres). The histogram in Fig. 14 illustrates the bathymetric distribution of the average maximum scour depths.

The deepest scours, averaging 1.2 m, occur between 140 m to 160 m, and the shallowest scours, averaging 0.5 m, occur between the 80 m and 100 m isobaths. Though there is a general trend toward deeper scours in deeper water, the distribution oscillates between the above extremes. The general trend is expected and may reflect the interaction of at least four factors: first, smaller bergs in shallower water will impact the seabed with lesser kinetic energy since their smaller surface area accumulates a lesser overall driving force from current or wind drag; secondly, the seabed may on the whole be stronger above 100 m water depth where dense lag gravels and the unconformity on Tertiary semi-consolidated bedrock lie close to the seabed; thirdly, sediment mobility in the shallower water may reduce scour depth by sedimentary infilling; and fourthly there is a greater chance of obtaining a rare deep scour in a long rather than a short series of events. There may be a shortage of rare deep scours over the Bank where iceberg flux is less than in deeper water in the core of the Labrador current where iceberg flux is greater.

The set of maximum scour depths in 2 km (10 minute) increments of survey line can be examined as a distribution of extreme values with distance or survey effort. This has been done for two series of values, one for the 100 m to 150 m bathymetric interval and the other for the 50 m to 100 m interval. The maximum depths are ranked in ascending order and plotted on extreme value distribution paper (Gumbel, 1958; Haan, 1977; Lewis, 1978) as shown in Fig. 15. The plotting position for the cumulative probability scale is calculated for each maximum depth value as the ratio of its rank to n + 1, where n is the number of values in the series. Both series plot as straight lines suggesting that the maximum ice-scour depths for the Grand Bank conform to and are reasonably well described by the extreme value distribution.

The plots basically organize and summarize the findings of maximum scour depths with respect to survey coverage. There is no time connotation other than that implied by the overall period in which these Holocene ice scours accumulated. Once established, the distribution allows one to discuss the expected scour depth for a given probability. For example in Fig. 15 there is, according to the upper scale, a .95 (95%) chance that all scours in a given survey line between the 100 m and the 150 m isobath will be less than 0.4 m deep. At a higher probability level there is a .99 (99%) chance that all scours encountered will be less than 2.7 m deep and so on for any desired cumulative probability level. The last example could be restated in terms of exceedance probability as follows: at the .99 cumulative probability level 1% (1 - .99 = .01) of the survey line is expected to contain scour depths equal to or in excess of 2.7 m or that there is a 5% exceedance probability (1-.95 = .05 (5%)) that scours will occur equal to or deeper than 0.4 m between the 100 m and 150 m isobaths on the northeastern Grand Bank.

The reciprocal of the exceedance probability yields the average number of sample units (2 km each) that are expected to be surveyed in order to encounter

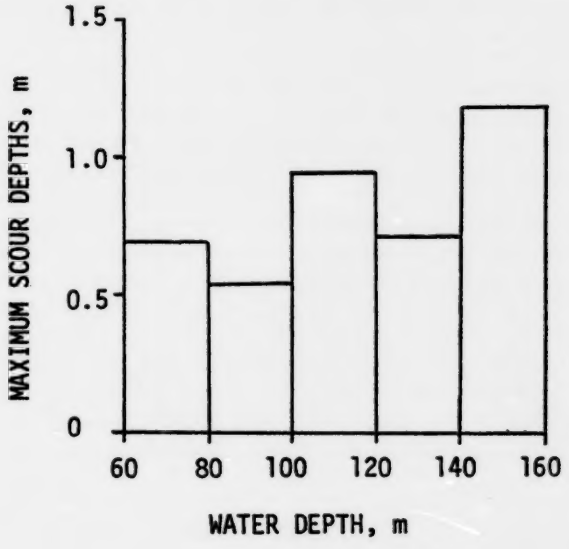


Fig. 14. Histogram of the average of maximum scour depths vs. water depth for the northeast Grand Bank area. The depths were measured in 43 sections of Huntec DTS profiles, each about 2 km long.

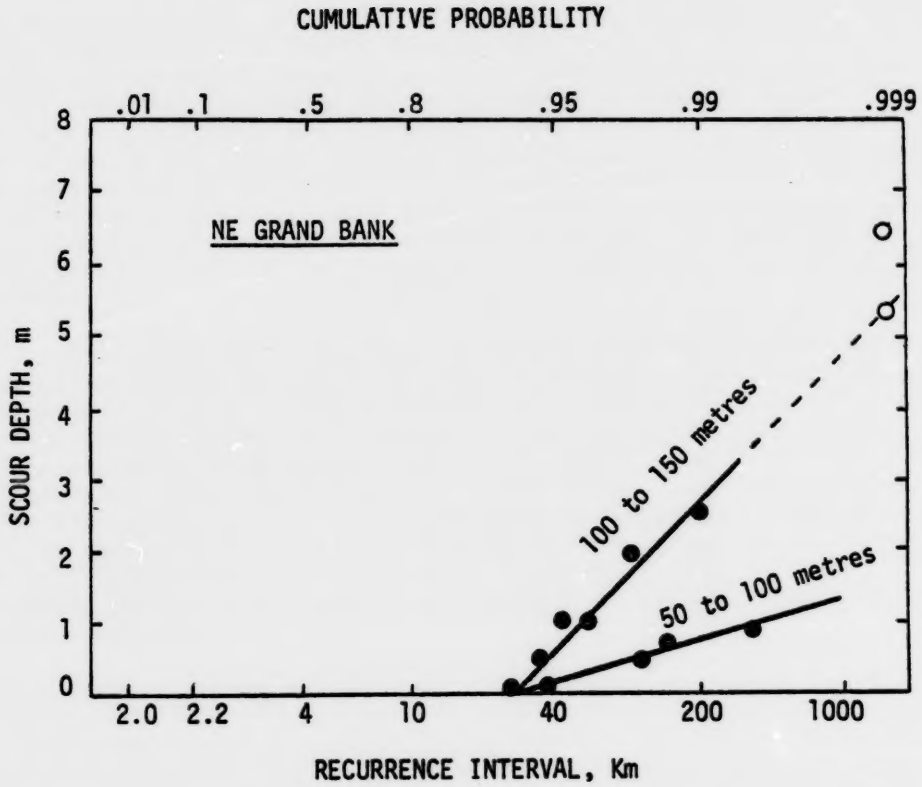


Fig. 15. Extreme value plots for maximum scour depths in the northeast Grand Bank area with points shown for scours deeper than 0.3 m, the minimum resolvable depth. Distribution for scours in the 50 to 100 m (158 samples) and 100 to 150 (100 samples) water depth intervals are plotted separately. The closed circles are data based on approximately 500 line km of Huntec DTS profiles from the regional survey east of 50° W and north of 44° N (Fig. 1). The open circles are the two maximum scour depths observed in an additional but independent 1100 line km of Huntec DTS profiles from the Hibernia - Ben Nevis research area (Fig. 6). The alignment (dashed) of closed circles in the 100 m to 150 m interval with one of the open circles suggests then two data sets are related, possibly drawn from the same distribution of extreme scour depths.

one exceedance. In Figure 15 for 1% exceedance (.99 cumulative probability) 100 sample units (1/.01) will be traversed while encountering one scour equalling or exceeding 2.7 m. The recurrence interval is written on the lower scale as 200 km because our sample units are each 2 km, approximately, of Huntec survey line (i.e. 2 km x 100 sample units = 200 km recurrence interval). The recurrence scale in kilometres is useful for roughly estimating the existing scour depths that might be encountered in a line (e.g. pipeline) of given length. For example we would expect to find one scour greater than 0.4 m in a 40 km line or greater than 2.7 m in a 200 km line. The distribution may be extended beyond existing data by extrapolating the fitted lines. Thus one scour equal to or deeper than 4.75 m is expected in a 1000 km line.

This extreme value model for maximum scour depths predicts the probability of values beyond its data base and can be tested by the findings of new data. This has been done and is shown by the open circles in Fig. 15. The model for the 100 m to 150 m isobath interval is based entirely upon samples from the HUDSON (Fig. 1) Huntec data, about 200 line km. A review of the POLARIS Huntec data in the same depth interval turned up 4 extreme scour depths greater than 1 m - 1.3, 1.5, 5.4 and 6.5 m - in 1100 km of survey. The two largest are plotted on Fig. 15 against a recurrence interval of 1300 km, the combined survey effort. The largest value 6.5 m, is not confirmed as an iceberg furrow on the sidescan record; it appears only as an isolated depression on the Huntec profile. The coincidence of the 5.4 m extreme, which is a confirmed iceberg furrow, with the extrapolated distribution line is a strong indication of the validity of the model.

The 50 m to 100 m distribution is substantially shallower than the 100 m to 150 m distribution as indicated by its lesser slope and as expected for the reasons discussed previously in connection with the bathymetric distribution of scour depths (Fig. 14). This suggests to us that until more is known about the sedimentary conditions or the exact nature of ice-seabed interaction in the shallowest water it would be prudent and conservative to use the more severe 100 m to 150 m extreme scour distribution in estimating burial depths or vertical protection for wellheads and pipelines at Hibernia where the water depth is 80 m.

SUMMARY AND CONCLUSIONS

Although analysis of the surficial geology, sediment stability and iceberg scouring of the northeast Grand Banks continues, it is possible to state the following summary and interim general conclusions from the evidence presented and cited.

1. A terrace with an upper elevation of 100 m trends northwest along the edge of the northeast Grand Bank in the Hibernia - Ben Nevis area and probably represents a late Wisconsinan low sea level stand about 15,000 to 20,000 years ago.

2. Quaternary sediments occur as thin discontinuous sand and gravel deposits over semi-consolidated Tertiary siltstones and sandstones. The Tertiary surface is unconformable. In depths shallower than 110 m it is also over-consolidated probably due to a previous history of subaerial exposure, erosion and desiccation.

3. A laterally-continuous deposit of fine sand, 2 to 5 m thick, occurs below the 100 m terrace in the sublittoral zone of the presumed late Pleistocene - early Holocene sea. The surface of this sand shows few bedforms and is thought to be relatively inactive under the modern hydrodynamic regime.

4. On the terrace, a relatively thin sand and gravel lag overlies the Tertiary bedrock surface. The gravel is veneered with sand ribbons which indicate movement of sediment in a southerly direction.

5. Upslope from the terrace and at the Hibernia wellsite area, a series of sub-parallel sand bars up to 3 m thick and 6 km wide parallel the north-northwest slope contours. The sand bars are separated by exposures of lag gravel and appear to be built upon the Tertiary surface or upon lag gravel overlying the Tertiary surface. Sampling and analysis of their internal structure, composition, and age are required to resolve their formation and the extent to which these features could be mobilized by extreme wave action and storm-generated currents or intrusion of ocean currents.

6. The presence of sand ribbons, sand waves and megaripples suggests north to south movement of sediment under the influence of current shear along the seabed on and above the 100 m terrace. This seabed appears to be influenced by modern storm waves (for example fresh sand ripples have been photographed) and it is postulated that infrequent episodes of strong bottom flows resulting from extreme winter storms or intrusions of the Labrador current are responsible for most of the observed current bedforms.

7. Two populations of ice scours can be distinguished. A population of relict ice scours probably of late Wisconsinan and early Holocene age occurs as a dense pattern of degraded furrows and pits on the seabed below present water depths of 110 metres approximately. The Holocene (or modern) population, in contrast, is sparse on the sea bottom and consists of relatively fresh-looking furrows and pits in all water depths examined (60 to 160 m). These ice scours probably accumulated within 10,000 years once sea level was high enough for icebergs to drift onto the Bank.

8. Histogram summaries of the Holocene ice scours based on measurements of features in sonograms and high resolution seismic profiles suggest that for the northeastern Grand Bank ice scours became narrower, shallower, less numerous and disturb a smaller percentage of the seabed in shoaler water. The scours are also less numerous in sand facies than in gravel facies at least for water depths under 100 metres. Scour widths range from 3 m to 124 m; depths are rarely greater than 1 metre. The deepest iceberg furrow discovered to date in the Hibernia area is 5.4 m; though an unconfirmed circular depression of 6.5 m occurs also: These extreme features are very rare. Their formation is probably equally infrequent. The occurrence of maximum scour depths appears to conform to the extreme value distribution which estimates the statistical probability of encountering large scours along transects of specified lengths. For example one exceedance of 0.7 and 2.7 metres is predicted on average for 100 km distance in the 50 - 100 m and 100 - 150 m bathymetri

intervals respectively. Until more is known about ice-seabed interaction and ice scour degradation processes it would be conservative to use the more severe extreme scour distribution in estimating burial depth or vertical protection for wellheads and pipelines at Hibernia.

9. From a consideration of Holocene ice scour distribution and morphology, sediment facies and geologic history and modern iceberg distribution, the following preliminary overview is postulated for the Hibernia region. Drifting icebergs are concentrated in and brought into the area by the Labrador Current as it flows around the northern and eastern margins of the Grand Bank. From this elongated source some bergs drift or are blown against the Bank where their keels touch ground on the southwesterly-shoaling bottom. The dragging and impacting action of keels on the bottom disturbs sediment and produces characteristic ice scours - linear furrows and circular pits. This process has probably persisted for some time as a series of intermittent randomly spaced events, possibly throughout the Holocene period after the post glacial rise of sea level and establishment of iceberg-supplying ocean currents. The upslope decrease in average scour depth, width, abundance and seabed disturbance is consistent with a situation where iceberg size and flux diminish down-source away from the Labrador current in a southwesterly direction toward the Bank. Smaller bergs which penetrate the Bank area are likely to do less work on the seabed due to their smaller keel size and lesser mass. The size and number of ice scours may be further diminished upslope by the occasional transport of sand under extreme currents in shallower water. Ice keel penetration depths above the 110 m isobath, approximately, may also be constrained by the presence of strong sediments associated with the over-consolidated surface of the Tertiary bedrock just beneath the seabed.

REFERENCES

Amos, C.L. and Barrie, J.V. 1980, Hibernia and Ben Nevis Seabed Study - Polaris V Cruise Report, June 1980, C-CORE Data Report 80-17, 40 pp.

Blenkarn, K.A. and Knapp, A.E. 1969, Ice Conditions on the Grand Banks, CIM Special Volume 10, The Ice Seminar, p. 61-72.

Chari, T.R. and Peters, G.R. 1981, Estimates of Iceberg Scour Depths. In; Symposium or Production and Transportation Systems for the Hibernia Discovery, St. John's.

Dinsmore, R.P., 1972, Ice and its Drift into the North Atlantic Ocean, Internation Commission for the Northwest Atlantic Fisheries Special Publication No. 8, p. 89-127.

Fader, G.B., 1980 Cruise Report, C.S.S. Hudson 80-010. Bedford Institute of Oceanography, Dartmouth, N.S.

Fader, G.B. and King, L.H. 1981, A Reconnaissance Study of the Surficial Geology of the Grand Banks of Newfoundland, Current Research Part A, Geological Survey of Canada, Paper 81-1A, p. 45-81.

Flemming, R.W. 1980, Sand Transport and Bedform Patterns on the Continental Shelf between Durhan and Port Elizabeth (Southwest African Continental Margin), Sedimentary Geology, 26, p. 179-205.

Gadd, P.E., Lavelle, J.W. and Swift, D.J.P. 1978, Estimates of Sand Transport on the New York Shelf Using Near-bottom Current Meter Observations. Journal of Sedimentary Petrology, 48, p. 239-252

Gumbel, E.J. 1958, Statistics of Extremes, Columbia University Press, New York, N.Y., 375 pp.

Gustajtis, K.A. 1979, Iceberg Scouring on the Labrador Shelf, Saglek Bank, C-CORE Technical Report 79-13, 89 pp.

Haan, C.T. 1977, Statistical Methods in Hydrology, The Iowa State University Press, Ames Iowa, 378 pp.

Harris, I.M. 1974, Iceberg Marks on the Labrador Shelf, Geological Survey of Canada Paper 74-30, p. 97-101.

Hutchins, R.W., McKeown, D.L. and King, L.H. 1976, A Deep Tow High Resolution Seismic System for Continental Shelf Mapping, Geoscience Canada, 3, p. 95-100

Jollymore, P.G., 1974, A Medium Range Side Scan Sonar for use in Coastal Waters; Design Criteria and Operational Experiences. In; Ocean '74 Proceedings of the IEEE International Conference on Engineering in the Ocean Environment Halifax, N.S., Vol. 2, New York, Institute of Electrical and Electronics Engineers, p. 108-114.

King, L.H. 1970, Surficial Geology of the Halifax-Sable Island Map Area, Department of Energy, Mines and Resources, Ottawa, Marine Sciences Branch Paper 1.

King, L.H. 1976, Relict Iceberg Furrows on the Laurentian Channel and Western Grand Banks, Canadian Journal of Earth Sciences, 13, p. 1082-1072.

King, L.H. and Fader, G.B. 1980, Seabed Conditions East of the Avalon Peninsula to the Virgin Rocks - Their Relationship to the Feasibility of a Pipeline from the Hibernia P-15 Wellhead Area to Newfoundland, Geological Survey of Canada, Open File Report 723.

Kovacs, A. and Mellor, M. 1974, Sea Ice Morphology and Ice as a Geologic Agent in the Southern Beaufort Sea, In; The Coast and Shelf of the Beaufort Sea, Reed, J.C. and Sater, J.E., eds., Arctic Institute North America, Arlington, Va., p. 113-161.

Lewis, C.F.M. 1978, The Frequency and Magnitude of Drift-Ice Groundings from Ice-Scour Tracks in the Canadian Beaufort Sea, In; POAC '77: The Fourth International Conference on Port and Ocean Engineering Under Arctic Conditions, St. John's, Newfoundland, Proceedings Vol. 1 Memorial University of Newfoundland, p. 568-579.

Lewis, C.F.M., MacLean, B. and Falconer, R.K.H., 1980, Iceberg Scour Abundance in Labrador Sea and Baffin Bay: A Reconnaissance of Regional Variability, Proceedings of the First Canadian Conference on Marine Geotechnical Engineering, Calgary, Alberta, p. 79-94.

Lewis, J. and Benedict, C.P. 1981, Icebergs on the Grand Bank: Oil and Gas Considerations, World Oil, January 1981.

McLaren, P., 1977, The Coasts of Eastern Melville and Western Byam Martin Islands: Coastal Processes and Related Geology of a High Arctic Environment. Unpublished Ph.D. Thesis, University of South Carolina, 304 pp.

Murray, J.F. 1969, The Drift, Deterioration and Distribution of Icebergs in the North Atlantic Ocean, CIM Special Vol. 10, The Ice Seminar, p. 3-18.

Pelletier, B.R and Shearer, J.M. 1972, Sea Bottom Scouring in the Beaufort Sea of the Arctic Ocean, 24th International Geological Congress, Section 8, Marine Geology and Geophysics, Montreal, p. 251-261.

Reimnitz, E. and Barnes, P.W., 1974, Sea Ice as a Geological Agent on the Beaufort Sea Shelf of Alaska, In; The Coast and Shelf of the Beaufort Sea, Proceedings of the Arctic Institute of North America Symposium on Beaufort Sea Coast and Shelf Research, p. 301-351.

Shearer, J.M. and Blasco, S.M., Further Observations of the Scouring Phenomena in the Beaufort Sea; Current Research Part A, Geological Survey of Canada, Paper 75-1A, p 483-493.

Swift, D.J.P. and Freeland, G.L. 1978, Current Lineations and Sand Waves on the Inner Shelf, Middle Atlantic Bight of North America, Journal of Sedimentary Petrology, 48, p. 1257-1266.

Swift, D.J.P., Freeland, G.L. and Young, R.A. 1979, Time and Space Distribution of Megaripples and Associated Bedforms, Middle Atlantic Bight, North American Atlantic Shelf, Sedimentology, 25, p. 389-406.

Wadhams, P. 1975, Sea Ice Morphology in the Beaufort Sea, Beaufort Sea Technical Report No. 36, Canada Dept. of Environment, Victoria, B.C., 66 pp.

Wahlgren, R.V. 1979, Ice Scour Tracks in Eastern MacKenzie Bay and North of Pullen Island, Beaufort Sea. Current Research, Part B, Geological Survey of Canada, Paper 79-1B, p. 51-62.

Walker, R.G., 1979, Facies Models 7. Shallow Marine Sands. In; ed. Facies Models. Geoscience Canada, Reprint Series 1, Walker, R.G. ed., p. 75 - 89.

ACKNOWLEDGEMENTS

The preliminary interpretation reported here is part of the Hibernia Sediments Program. We gratefully acknowledge the other program participants, G.B. Fader, L.H. King and C.L. Amos of the Atlantic Goescience Centre for their support, co-operation and critical review of this manuscript. We also thank S. d'Apollonia for exhaustive scour analysis of seismic records, L. Nicks for her detailed surficial geological interpretation and C. Lynas for compilation of the geological maps. A large portion of the seismic and sample data collected was through both the logistic support and data collection of Mobil Oil Canada. The success of the data collection should be largely credited to the Captain and crew of the MV Polaris V and the full co-operation of McElhanney Surveying and Engineering.